Vectorized CRTM for JPSS Applications

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Abstract

The **Community Radiative Transfer Model** (**CRTM**) is a fast radiative transfer model for satellite radiometer radiance calculations, and is also used for the direct assimilation of radiances for numerical weather prediction models (NWP). However, the CRTM (v2.3) employed in current Gridpoint Statistical Interpretation (GSI) in data assimilation is a scalar radiative transfer model in which only microwave surface emissivity is polarized. Neglecting other Stokes components will cause significant errors in simulating or assimilating the radiances in many spectral regions including the UV.

For this PGRR project, a new and enhanced CRTM solver has been developed to solve this problem. In addition, more absorption gases are included, and wavelength-dependent surface reflectance are introduced. Rayleigh scattering optical depth and depolarization ratio are used in accurate calculations, and the effect of rotational Raman scattering will also be considered. The optical properties for aerosols and clouds are extended to the UV region. Major efforts are devoted to tangent linear (TL) and adjoint model programming. This new version of CRTM (currently v3.0 alpha) is expected to greatly improve the radiance simulations at the Top of Atmosphere (TOA) observed by OMPS and other radiometers. This project will pave the way for the use of OMPS radiance data in global and regional NWP models. The impacts on weather forecasting are expected to be positive. It may also have broader impacts on satellite radiance simulation and assimilation for other radiometers.

Introduction

- The Community Radiative Transfer Model (CRTM) is a fast satellite sensor-based radiative transfer model. It supports more than 100 sensors including sensors on most meteorological and remote sensing satellites. The CRTM is composed of four important modules for gaseous transmittance, surface emission and reflection, cloud and aerosol absorption and scatterings, and solvers for radiative transfer. The CRTM was designed to meet Numerical Weather Prediction (NWP) and other users' needs. Many options are available for users to choose: input surface emissivity; select a subset of channels for a given sensor; turn on/off scattering calculations; compute radiance at aircraft altitudes; compute aerosol optical depth only; and threading of the CRTM, and others.

- The CRTM forward model is used to simulate satellite measured radiance, which can be used to verify measurement accuracy, uncertainty, and long-term stability (Figure 1). The K-matrix module is used to compute Jacobian values (i.e. radiance derivative to geophysical parameters), which is used for the inversion processing in retrieval and radiance assimilations. Tangent-linear and adjoint modules are also often applied to radiance assimilation. The CRTM is a FORTRAN library for users to link to their own code, instead of a graphic user interface. At the CRTM initialization, user selects the sensor/sensors and surface emissivity/reflectance look-up tables. The gaseous transmittance describes atmospheric gaseous absorption, so that one can utilize remote sensing information in data assimilation/retrieval systems for atmospheric temperature, moisture, and trace gases such as CO_2, O_3, N_2O, CO, and CH_4. The aerosol module is fundamental to acquire aerosol type and concentration for studying air quality. The cloud module contains optical properties of six cloud types, providing radiative forcing information for weather forecasting and climate studies. The CRTM surface model includes surface static and atlas-based emissivity/reflectivity for various surface types. Two radiative transfer solvers have been implemented into the CRTM. The advanced matrix operator method (AMOM) is chosen as a baseline. The successive order of interaction (SOI) radiative transfer developed at the University of Wisconsin, has also been implemented in the CRTM.

Background and Motivation

- Ozone is a gas that occurs naturally in trace amounts in the earth's atmosphere, distributed mostly in the lower and middle stratosphere. It plays a critical role in the series of intricate feedback mechanisms that dynamically link the troposphere and the stratosphere. It blocks most of the harmful Ultraviolet Solar radiation from reaching the Earth's surface and impacts air quality near the surface. Daily measurements of the ozone distribution is an important component of a more realistic treatment of the stratosphere in operational weather forecast. This is especially true in the vicinity of jet streams at the mid and high latitudes, which play a major role in the formation and steering of tropospheric weather systems, including large-scale thunderstorm complexes and hurricanes. Improved forecasting of jet streams should lead to improved long-term forecasting of tropospheric weather. NWP centers worldwide are extending their data assimilation and forecasting codes to provide a more realistic treatment of the stratosphere, thus the need for direct assimilation of OMPS UV radiances.

- Currently, the assimilation of ozone information from satellites is carried out only in retrieval space. What this means is that from the direct radiance measurements by the OMPS instrument, ozone is retrieved based on theoretical models and a number of assumptions. This becomes the retrieved ozone product used by NWP, but unfortunately also inherits uncertainties in the retrieval process. As a result, the assimilation of ozone retrieval products has two major drawbacks. One is that retrieval is an ill-posed problem and the result may depend on the first guess (or assumptions in the retrieval). The other is the inconsistency between the ozone retrievals from different satellite instruments, for example, from OMPS and CrIS. In addition, the spectral radiance measurements contain rich information about the atmospheric chemistry which may be lost after retrievals. Therefore, the NWP community prefers to assimilate the OMPS radiances directly in the weather models.

- In addition to the simulation and assimilation of UV radiances, there is a broader need for a fast vectorized/polarized radiative transfer model in other spectral regions. Thus the outcome may have additional impacts.

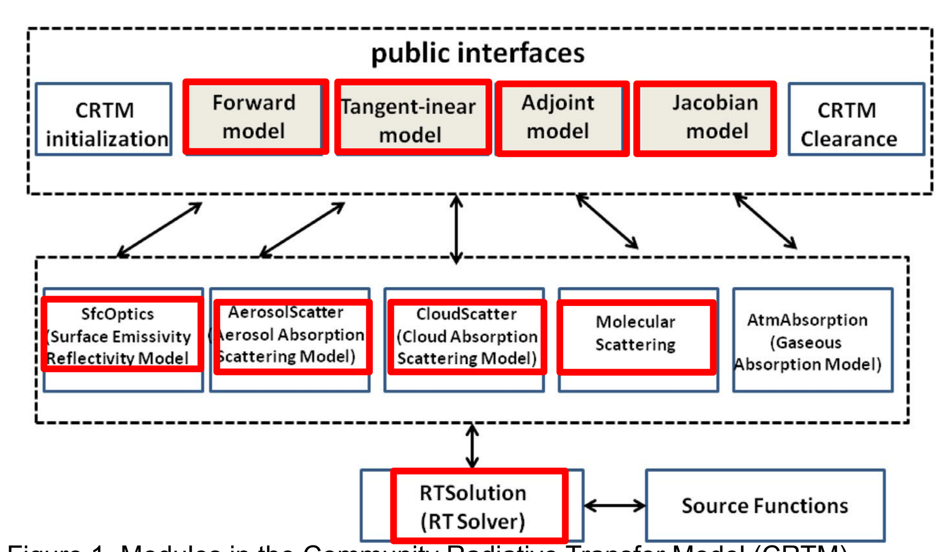
Project Goals

The primary goal of this project is to develop the vectorized CRTM capability so that OMPS UV measurements can be directly assimilate in numerical weather prediction models for weather forecasting. This requires substantial development for a new version of the CRTM that can treat polarized radiation correctly. This new capability will enable the CRTM to assimilate daily measurements of the ozone field from OMPS. It is also possible that this new capability can be extended to other radiometers.

A secondary goal is to use the vectorized CRTM for more accurate simulation of satellite radiometer radiances with polarization effect, which may be applicable in multiple spectral bands of a variety of radiometers, including VIIRS, CrIS, and ATMS.

Vectorized CRTM Theoretical Basis

An approach is introduced to retain the reciprocity principle in radiative transfer and applies a Taylor expansion of analytic transmittance and reflection matrices for a base optical depth together with a doubling-adding method beyond the base in the vectorized Community Radiative Transfer Model (CRTM). The value of the base optical depth depends on the maximum absolute value of the phase matrix elements. In comparison with other forward radiative transfer models, the extended vectorized CRTM agrees well with those models. The computational efficiency among the CRTM and those models is comparable. The tangent-linear and adjoint modules of the vectorized CRTM can be used for assimilating microwave, infrared, visible and ultraviolet sensor radiances (Liu and Cao, 2019).



Modules required code changes for the vectorized CRTM

Using polarization is a new option, with minimal impacts on existing users

Figure 1. Modules in the Community Radiative Transfer Model (CRTM)

The vectorized radiative transfer equation is the same as the scalar radiative transfer except using the Stokes vector (with 4 components: radiance, polarization difference, the plane of polarization and the ellipticity of the electromagnetic wave) to replace intensity. Single phase function element is replaced by a 4 by 4 matrix, which may destroy the symmetry used in the scalar radiative transfer. Generally speaking, the reciprocity principle is no longer valid, which means that the transmittance matrix at the layer top is different from the transmittance at the bottom. This is the same true for the reflection matrix.

$$\mu_i \begin{bmatrix} \frac{d\mathbf{I_m}(\tau,\mu_i)}{d\tau} \\ \frac{-d\mathbf{I}'_m(\tau,-\mu_i)}{d\tau} \end{bmatrix} = \begin{bmatrix} \mathbf{I_m}(\tau,\mu_i) \\ \mathbf{I}'_m(\tau,-\mu_i) \end{bmatrix} - \varpi \sum_{j=1}^{N} \begin{bmatrix} \mathbf{P_m}(\tau,\mu_i,\mu_j) & \mathbf{P}'_m(\tau,\mu_i,-\mu_j) \\ \mathbf{P}'_m(\tau,\mu_i,-\mu_j) & \mathbf{P_m}(\tau,\mu_i,\mu_j) \end{bmatrix} \times \begin{bmatrix} \mathbf{I_m}(\tau,\mu_j) \\ \mathbf{I}'_m(\tau,-\mu_j) \end{bmatrix} w_j - \begin{bmatrix} \mathbf{S_m}(\tau,\mu_i,-\mu_0) \\ \mathbf{S}'_m(\tau,-\mu_i,-\mu_0) \end{bmatrix}$$

Vectorized radiative transfer equation can be written in the same form as for the scalar radiative transfer by increasing number of elements from n_Angles to n_Stokes x n_Angles, where n_Stokes represents the number of Stokes components (< = 4). It implies that the reciprocity principle can also be valid for vectorized radiative transfer so that transmission and reflection matrices from the top and from the bottom of a homogeneous layer can be the same. This considerably simplifies code implementation and saves half of the computational time associated with scattering. The adding method of the CRTM ADA can be used for vectorized radiative transfer by increasing the number of elements from n_Angles to n_Stokes x n_Angles (Liu & Cao, 2019).

The CRTM v3.0 alpha Release

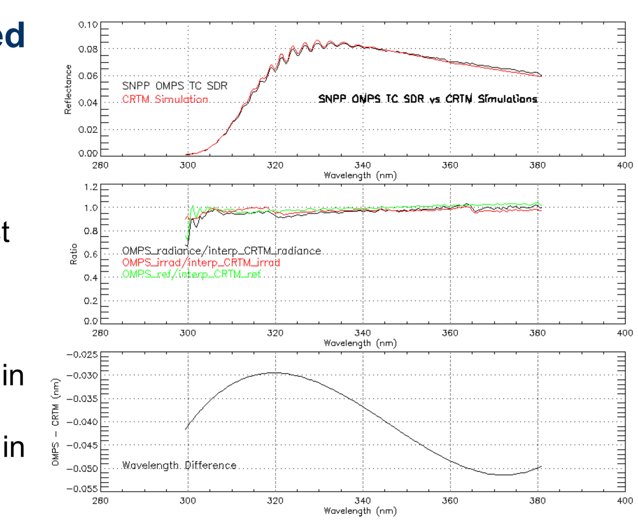
The vectorized Community Radiative Transfer Model (CRTM v3.0 alpha) has been released (11/27/2019) , which is a major milestone achieved. CRTM 3.0 alpha is under testing at the NOAA/STAR and JCSDA .

```
cd libsrc
make clean
make -f Makefile_intel              or   make -f Makefile_gfortran
cd ../
cd run_operational
make clean
make intel                         or make gfortran

VCRTM_Model_UV

output file
u.omps-tc_npp_sub_channel.out

You can use the outputs from the RTSolution
    REAL(fp) :: Radiance
    REAL(fp) :: Brightness_Temperature
    REAL(fp) :: Stokes(4)
    REAL(fp) :: SolarIrradiance

The OMPS   "N value" will be   (note "N" isn't divided by cosine of solar zenith angle!!)
   N_value(1:n_channels) = RTSolution(:,1)%Radiance/RTSolution(:,1)%SolarIrradiance

You can change the Test_Case in line 84
! PURPOSE: Tests for CRTM Version 3 alpha
!    This CRTM Version 3 alpha has been extended from CRTM Version 2.3x. By default, users run current CRTM operational 2.3x without any changes
!    (same results and negligible difference in computational time, except for the bug-fixed in K-matrix for azimuthal dependent scattering radiance
!    (e.g. visible channels).
!
!    To do the polarized radiance calculations, users need to provide polarized tables for cloud and aerosol scattering tables. For this testing code,
!    we use the LUT for spherical particles as a place holder. A more detailed LUT including non-spherical particles will be available. From version 3,
!    LUT includes "back scattering coefficient" for active sensors.
!
!  This code can go through following test cases. Users can define their own applications.
 ! = 1 cris_n20 (FWD); CRTM version 2x
 ! = 2 u.omps-tc_npp (FWD); CRTM version 3
 ! = 3 u.omps-tc_npp (FWD, K-matrix) for selected channels used in ozone retrieval or potential radiance assimilation, CRTM version 3

!    Quanhua (Mark) Liu, November 26, 2019
!    NOAA/NESDIS Center for Applications and Research
!    College Park, Maryland, United States
!    quanhua.liu@noaa.gov
```

Release notes in the readme file

Preliminary Results

Comparison of calculated vs. OMPS observed radiances:



- OMPS and CRTM TC reflectance agree well (upper panel and middle panels). The ratio of the measured and CRTM reflectance (green) agree except for the first two channels of wavelengths (<300 nm).

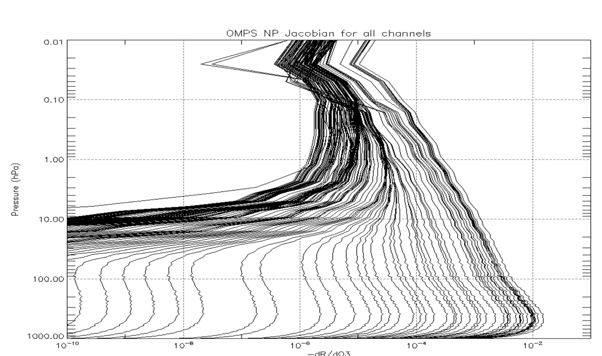
- Wavelength difference between OMPS measurements and the CRTM (static) (low panel) need to be resolved in the near future. Additional validation will be performed once the NOAA-20 OMPS achieved validated maturity in Spring 2020.

OMPS and CrIS Ozone channel Jacobian

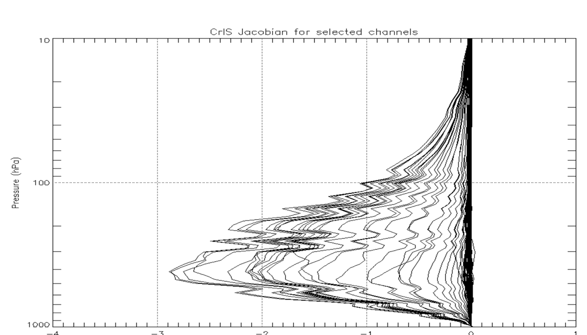
- OMPS NP measurements show good sensitivity to ozone in stratosphere and troposphere. However, the vertical resolution of OMPS NP measurements on ozone is coarse. The negative radiance sensitivities implies that increasing ozone reduces backscattered solar radiation.

- Vectorized CRTM shows good sensitivity of CrIS to ozone in the troposphere. The maximum sensitivity is around 400 hPa.

- Combining both CrIS and OMPS NP as well as OMPS TC observations allows better consistency between OMPS and CrIS application for better performance.



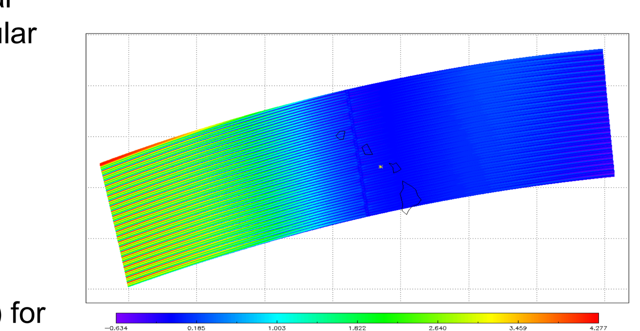
OMPS Jacobian



CrIS Jacobian

Future Work

- Assessment of the vectorized CRTM in NOAA/GSI radiance assimilations or other NWP models, and experimental assimilation of JPSS OMPS radiance (looking for collaborators)
- Additional JPSS OMPS radiance simulations (ongoing)
- Look-up tables updates for cloud and aerosol optical properties; polarized surface BRDF models; molecular scattering module
- Addressing OMPS wavelength shift, possibly using ML/AI
- Other studies: using the vectorized CRTM for simulation, including model comparisons (with 6SV) for simulating polarization effect in the 0.4μm band (M1) of VIIRS.



Polarization in NOAA-20 VIIRS M1

Summary

The vectorized CRTM with polarization capability has been developed and its theoretical basis has been documented in journal publications. Although the main purpose of this version is for the direct radiance assimilation of OMPS UV radiances, it may have broader applications in forward calculations and in other spectrum as well. Initial testing shows that the performance of this vectorized CRTM is faster than similar vectorized models, and therefore can be used for NWP.

Forward calculations of radiances are being compared with OMPS observations, and the Jasobian for the OMPS and CrIS ozone channels are investigated. The initial version (version 3.0 alpha) was released on November 27, 2019 and the next version is expected to be released in July 2020. Users are encouraged to participate in the testing. Additional validation of the vectorized CRTM is currently being carried out in several applications.

References:

[1] Liu, Q. and C. Cao, 2019: Analytic expressions of the Transmission, Reflection, and source function for the community radiative transfer model, Journal of Quantitative Spectroscopy and Radiative Transfer, 226, 115-126, https://doi.org/10.1016/j.jqsrt.2019.01.019.

[2] Liu Q , Weng F . Advanced doubling-adding method for radiative transfer in planetary atmosphere. J. Atmos. Sci. 2006;63:3459–65 .

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